

II. "On the Action of Heat on Gravitating Masses." By WILLIAM CROOKES, F.R.S. &c. Received August 12, 1873.

(Abstract.)

The experiments recorded in this paper have arisen from observations made when using the vacuum-balance, described by the author in his paper "On the Atomic Weight of Thallium"*, for weighing substances which were of a higher temperature than the surrounding air and the weights. There appeared to be a diminution of the force of gravitation; and experiments were instituted to render the action more sensible, and to eliminate sources of error.

In an historical *résumé* of the state of our knowledge on the subject of attraction or repulsion by heat, it is shown that in 1792 the Rev. A. Bennet recorded the fact that a light substance delicately suspended in air was attracted by warm bodies: this he ascribed to air-currents. When light was focused, by means of a lens, on one end of a delicately suspended arm, either in air or in an exhausted receiver, no motion could be perceived distinguishable from the effects of heat.

Laplace spoke of the repulsive force of heat. Libri attributed the movement of a drop of liquid along a wire heated at one end, to the repulsive force of heat; but Baden Powell did not succeed in obtaining evidence of repulsion by heat from this experiment.

Fresnel described an experiment by which concentrated solar light and heat caused repulsion between one delicately suspended and one fixed disk. The experiment was tried in air of different densities; but contradictory results were obtained under apparently similar circumstances at different times, and the experiments were not proceeded with.

Saigey described experiments which appeared to prove that a marked attraction existed between bodies of different temperatures.

Forbes, in a discussion and repetition of Trevelyan's experiment, came to the conclusion that there was a repulsive action exercised in the transmission of heat from one body into another which had a less power of conducting it.

Baden Powell, repeating Fresnel's experiment, explained the results otherwise than as due to repulsion by heat. By observing the *descent* of the tints of Newton's Rings between glass plates when heat was applied, Baden Powell showed that the interval between the plates increased, and attributed this to a repulsive action of heat.

Faye introduced the hypothesis of a repulsive force of heat to account for certain astronomical phenomena. He described an experiment to show that heat produced repulsion in the luminous arc given by an induction-coil in rarefied air.

The author describes numerous forms of apparatus successively more

* Phil. Trans. 1873, vol. clxiii. p. 277.

and more delicate, which enabled him to detect and then to render very sensible an action exerted by heat on gravitating bodies, which is not due to air-currents or to any other known form of force.

The following experiment with a balance made of a straw beam with pith-ball masses at the ends enclosed in a glass tube and connected with a Sprengel pump, may be quoted from the paper:—

“The whole being fitted up as here shown, and the apparatus being full of air to begin with, I passed a spirit-flame across the lower part of the tube at *b*, observing the movement by a low-power micrometer; the pith ball (*a, b*) descended slightly, and then immediately rose to considerably above its original position. It seemed as if the true action of the heat was one of attraction, instantly overcome by ascending currents of air.

“31. In order to apply the heat in a more regular manner, a thermometer was inserted in a glass tube, having at its extremity a glass bulb about $1\frac{1}{2}$ inch in diameter; it was filled with water and then sealed up. . . The water was kept heated to 70° C., the temperature of the laboratory being about 15° C.

“32. The barometer being at 767 millims. and the gauge at zero, the hot bulb was placed beneath the pith ball at *b*. The ball rose rapidly; as soon as equilibrium was restored, I placed the hot-water bulb above the pith ball at *a*, when it rose again, more slowly, however, than when the heat was applied beneath it.

“33. The pump was set to work; and when the gauge was 147 millims. below the barometer, the experiment was tried again; the same result, only more feeble, was obtained. The exhaustion was continued, stopping the pump from time to time, to observe the effect of heat, when it was seen that the effect of the hot body regularly diminished as the rarefaction increased, until when the gauge was about 12 millims. below the barometer the action of the hot body was scarcely noticeable. At 10 millims. below it was still less; whilst when there was only a difference of 7 millims. between the barometer and the gauge, neither the hot-water bulb, the hot rod, nor the spirit-flame caused the ball to move in an appreciable degree. The inference was almost irresistible that the rising of the pith was only due to currents of air, and that at this near approach to a vacuum the residual air was too highly rarefied to have power in its rising to overcome the inertia of the straw beam and the pith balls. A more delicate instrument would doubtless show traces of movement at a still nearer approach to a vacuum; but it seemed evident that when the last trace of air had been removed from the tube surrounding the balance—when the balance was suspended in empty space only—the pith-ball would remain motionless, wherever the hot body were applied to it.

“34. I continued exhausting. On next applying heat, the result showed that I was far from having discovered the law governing these

phenomena; the pith ball rose steadily, and without that hesitation which had been observed at lower rarefactions. With the gauge 3 millims. below the barometer, the ascension of the pith when a hot body was placed beneath it was equal to what it had been in air of ordinary density; whilst with the gauge and barometer level its upward movements were not only sharper than they had been in air, but they took place under the influence of far less heat; the finger, for example, instantly sending the ball up to its fullest extent."

A piece of ice produced exactly the opposite effect to a hot body.

Numerous experiments are next given to prove that the action is not due to electricity.

The presence of air having so marked an influence on the action of heat, an apparatus was fitted up in which the source of heat (a platinum spiral rendered incandescent by electricity) was inside the vacuum-tube instead of outside it as before; and the pith balls of the former apparatus were replaced by brass balls. By careful management and turning the tube round, the author could place the equipoised brass pole either over, under, or at the side of the source of heat. With this apparatus it was intended to ascertain more about the behaviour of the balance during the progress of the exhaustion, both below and above the point of no action, and also to ascertain the pressure corresponding with this critical point.

After describing many experiments with the ball in various positions with respect to the incandescent spiral, and at different pressures, the general result is expressed by the statement that the tendency in each case was to bring the centre of gravity of the brass ball as near as possible to the source of heat, when air of ordinary density, or even highly rarefied air, surrounded the balance. The author continues:—

"44. The pump was then worked until the gauge had risen to within 5 millims. of the barometric height. On arranging the ball above the spiral (and making contact with the battery), the attraction was still strong, drawing the ball downwards a distance of 2 millims. The pump continuing to work, the gauge rose until it was within 1 millim. of the barometer. The attraction of the hot spiral for the ball was still evident, drawing it down when placed below it, and up when placed above it. The movement, however, was much less decided than before; and in spite of previous experience (33, 34) the inference was very strong that the attraction would gradually diminish until the vacuum was absolute, and that then, and not till then, the neutral point would be reached. Within one millimetre of a vacuum there appeared to be no room for a change of sign.

"45. The gauge rose until there was only half a millimetre between it and the barometer. The metallic hammering heard when the rarefaction is close upon a vacuum commenced, and the falling mercury only occasionally took down a bubble of air. On turning on the battery cur-

rent, there was the faintest possible movement of the brass ball (towards the spiral) in the direction of attraction.

“46. The working of the pump was continued. On next making contact with the battery, no movement could be detected. The red-hot spiral neither attracted nor repelled. I had arrived at the critical point. On looking at the gauge I saw it was level with the barometer.

“47. The pump was now kept at full work for an hour. The gauge did not rise perceptibly; but the metallic hammering sound increased in sharpness, and I could see that a bubble or two of air had been carried down. On igniting the spiral, I saw that the critical point had been passed. The sign had changed, and the action was faint but unmistakable *repulsion*. The pump was still kept going, and an observation was taken from time to time during several hours. The repulsion continued to increase. The tubes of the pump were now washed out with oil of vitriol*, and the working was continued for an hour.

“48. The action of the incandescent spiral was now found to be energetically *repellent*, whether it was placed above or below the brass ball. The fingers exerted a repellent action, as did also a warm glass rod, a spirit-flame, and a piece of hot copper.”

In order to decide once for all whether these actions really were due to air-currents, a form of apparatus was fitted up which, whilst it would settle the question indisputably, would at the same time be likely to afford information of much interest.

By chemical means the author obtained in an apparatus a vacuum so nearly perfect that it would not carry a current from a Ruhmkorff's coil when connected with platinum wires sealed into the tube. In such a vacuum the repulsion by heat was still found to be decided and energetic.

An experiment is next described, in which the rays of the sun, and then the different portions of the solar spectrum, are projected on to the delicately suspended pith-ball balance. *In vacuo* the repulsion is so strong as to cause danger to the apparatus, and resembles that which would be produced by the physical impact of a material body.

Experiments are next described in which various substances were used as the gravitating masses. Amongst these are ivory, brass, pith, platinum, gilt pith, silver, bismuth, selenium, copper, mica (horizontal and vertical), charcoal, &c.

The behaviour of a glass beam with glass ends in a chemical vacuum, and at lower exhaustion, is next accurately examined when heat is applied in different ways.

On suspending the light index by means of a cocoon fibre in a long glass tube furnished with a bulb at the end, and exhausting in various ways, the author finds that the attraction to a hot body in air, and the repulsion from a hot body *in vacuo* are rendered still more apparent.

* This can be effected without interfering with the exhaustion.

Speaking of Cavendish's celebrated experiment, the author says that he has experimented for some months on an apparatus of this kind, and gives the following outline of one of the results he has obtained :—

“A heavy metallic mass, when brought near a delicately suspended light ball, attracts or repels it under the following circumstances :—

“I. *When the ball is in air of ordinary density.*

a. If the mass is *colder* than the ball, it *repels* the ball.

b. If the mass is *hotter* than the ball, it *attracts* the ball.

“II. *When the ball is in a vacuum.*

a. If the mass is *colder* than the ball, it *attracts* the ball.

b. If the mass is *hotter* than the ball, it *repels* the ball.”

The author continues:—“The density of the medium surrounding the ball, the material of which the ball is made, and a very slight difference between the temperatures of the mass and the ball, exert so strong an influence over the attractive and repulsive force, and it has been so difficult for me to eliminate all interfering actions of temperature, electricity, &c., that I have not yet been able to get distinct evidence of an independent force (not being of the nature of heat) urging the ball and the mass together.

“Experiment has, however, showed me that, whilst the action is in one direction in dense air, and in the opposite direction in a vacuum, there is an intermediate pressure at which differences of temperature appear to exert little or no interfering action. By experimenting at this critical pressure, it would seem that such an action as was obtained by Cavendish, Reich, and Baily should be rendered evident.”

After discussing the explanations which may be given of these actions, and showing that they cannot be due to air-currents, the author refers to evidences of this repulsive action of heat, and attractive action of cold, in nature. In that portion of the sun's radiation which is called heat, we have the radial repulsive force, possessing successive propagation, required to explain the phenomena of comets and the shape and changes of the nebulae. To compare small things with great—to argue from pieces of straw up to heavenly bodies—it is not improbable that the attraction, now shown to exist between a cold and a warm body, will equally prevail when, for the temperature of melting ice is substituted the cold of space, for a pith ball a celestial sphere, and for an artificial vacuum a stellar void. In the radiant molecular energy of cosmical masses may at last be found that “agent acting constantly according to certain laws,” which Newton held to be the cause of gravity.